ON-ORBIT RESULTS FROM THE TACSAT-2 ACTD TARGET INDICATOR EXPERIMENT AIS PAYLOAD

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ABSTRACT

As part of the US Department of Defense's Operationally Responsive Space (ORS) initiative, the Naval Research Laboratory (NRL) developed the Target Indicator Experiment (TIE) payload for the TacSat-2 spacecraft, which was launched 16 December, 2006 on a Minotaur 1 launch vehicle from Wallops Island, Virginia. The TIE payload was an improved version of the primary payload developed for the TacSat-1 spacecraft. One of the main enhancements was the addition of a software definable radio receiver and demodulator for the collection of the Automated Identification System (AIS) signal now required globally on large ships for maritime safety and security. While several systems have been proposed, TacSat-2 was the first small satellite to successfully collect AIS signals from space. This paper presents an overview of the design of the TIE payload AIS system, the collection experiments that were performed during the life of the spacecraft, the results of those experiments, samples of the data collected, and recommendations for future systems**.**

1. INTRODUCTION

1.1. TacSat-2 ACTD Overview

The TacSat-2 spacecraft, which evolved from the TechSat-21 and Roadrunner programs, was built and operated by the Air Force Research Laboratory (AFRL). In order to obtain the funding necessary to complete the program, four Space Test Program payloads were added to the mission. In addition, TacSat-2 was an approved FY 2005 Advanced Concept Technology Demonstration (ACTD). By the time it was launched the spacecraft carried thirteen unique payloads and experimental subsystems, some of which doubled as mission critical, non-redundant spacecraft systems. This mix of tactical, scientific and experimental payloads resulting in conflicting requirements, goals and expectations. Furthermore, the large number of conflicting operational configurations and payload desires, combined with the spacecraft's power constraints, and limited downlink availability made spacecraft operations extremely challenging. Finally, because TacSat-2 was exceptionally power constrained, experimentation time for each payload was very limited.

The primary mechanism for TacSat-2 to meet the objectives of the ACTD was through a joint military utility assessment (JMUA). If the assessment concluded that there was military utility, then the spacecraft would be transitioned to operational use. The two primary operational payloads used to assess the military utility of TacSat-2 were an optical imager and the TIE payload.

Due to policy issues and technical delays certain aspects of the JMUA were not fully explored. In addition, high level interest from the US Coast Guard (USCG), US Navy, and other organizations in the TIE AIS payload warranted additional experimentation. These conditions resulted in the approval of an Extended User Evaluation (EUE), which would complete the JMUA. One of the objectives of this EUE was to assess the potential utility of AIS capabilities in coordination with the Maritime Domain Awareness (MDA) Community.

The USCG was a major supporter of the EUE. They desired to use the TIE AIS data to improve spectrum protection in the future for reception of AIS signals from space. The spectrum protection issues dealt with the significant and growing interference threat to the successful reception of AIS signals from space. The USCG had been working with the US Federal Communications Commission (FCC) and the International Telecommunications Union (ITU) for several years to clear the two maritime AIS frequencies for exclusive AIS use. However, before this frequency allocation action could be taken, the FCC wanted a demonstration of the feasibility of receiving AIS signals from space. Thus, a key expectation from the EUE was the investigation of interference caused by the use of AIS frequencies by other radio services, and AIS signal saturation caused by excessive AIS transmissions. The EUE ended on 27 November, 2007 when contact with the spacecraft was lost, and the operations team was

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unable to recover the vehicle. Not all of the EUE objectives were accomplished at least in part due to the unexpected loss of the spacecraft.

1.2. TIE Payload Overview

The TIE payload, which was sponsored by the Office of Naval Research, DoD ACTD process, Director Defense Research & Engineering, and the Office of the Secretary of Defense/Office of Force Transformation, was designed to perform real time signal geo-location of radio frequency (RF) signals from 0.5 to 18.0 GHz using space and air based collection platforms. Real time commanding and downlinks were performed using an ultra high frequency (UHF) radio. The TIE payload was also capable of collecting the AIS signal in the VHF maritime band.

The TIE payload consisted of multiple electronic boxes and antennas, and the associated wire harnesses and RF cables. The main components necessary for the collection of AIS signals were the TIE Controller Unit (TCU), the RF Front End (RFFE) and multiple AIS antenna elements. The electronics boxes combined commercial off-the-shelf (COTS) components that had been modified for use in space, commercial boards and parts that had been re-packaged for spaceflight, and space qualified components packaged specifically for this experiment. The antennas also utilized a mix of COTS components that had been screened for use in space, and elements that had been designed and produced specifically for the TIE.

1.3. AIS System Design

The TIE AIS receiver system was implemented as a software reconfigurable radio to optimize its performance and flexibility. New radio software could be uploaded to the spacecraft to change and improve its performance. Unfortunately, the TIE team did not have the resources to engage in a significant level of reprogramming and upgrading prior to the end of the mission. The modifications that were completed were limited to capturing raw, undemodulated, sampled RF data. These changes, and the sequence of experiments being conducted at the end of the mission were leading to some possible improvements in the software radio algorithm.

The AIS antennas were deployable whips that used a legacy tapered hinge-lock mechanism, and were mounted on and restrained by the solar array as shown in Figs. 1 and 2. These antenna elements were electrically combined into a directional phased array. Creating a phased array with significant gain or directivity at VHF frequencies requires significant physical separation of the elements. Taking advantage of the size of the TacSat-2 solar arrays facilitated operating at the VHF marine frequencies, and allowed the beam forming electronics to create a beam with some amount of directivity and about 10dB of gain as shown in Fig. 3.

The phased array, as implemented, represented a significant compromise from the original design due to mechanical interferences between some of the elements of the array and the spacecraft bus. Two elements were completely removed and one was shortened to a "T" configuration. The antenna pattern for the original design is shown in Fig. 4. Later analysis showed that the modifications to the array, and the affects of coupling the array to adjacent structures did not significantly degrade the pattern from the ideal. Detailed on-orbit antenna pattern measurements were not taken, and would have been challenging at these frequencies with the resources available to the TIE team. However, plotting the AIS data that was collected demonstrated that the antenna pattern was generally consistent with the pattern predicted by the analysis software.

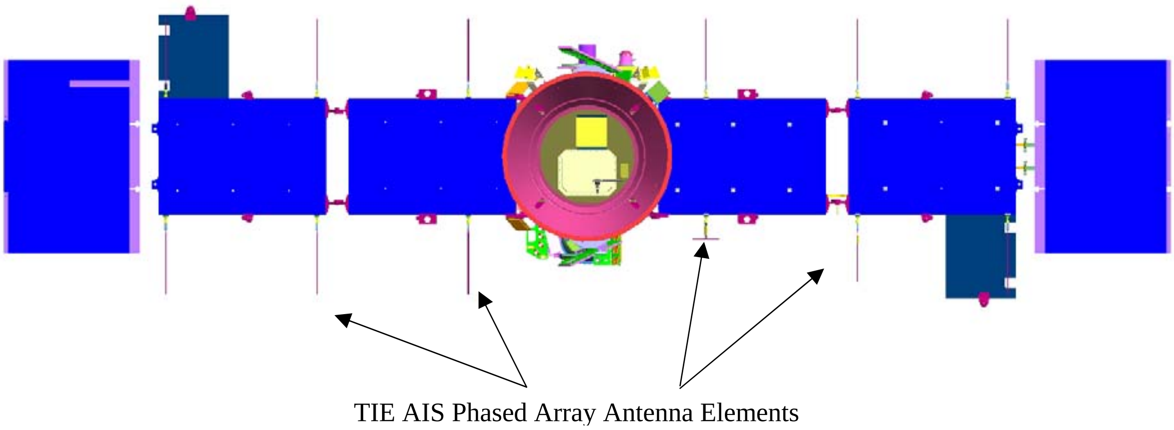

Figure 1. TIE AIS Antennas on the Deployed Solar Arrays

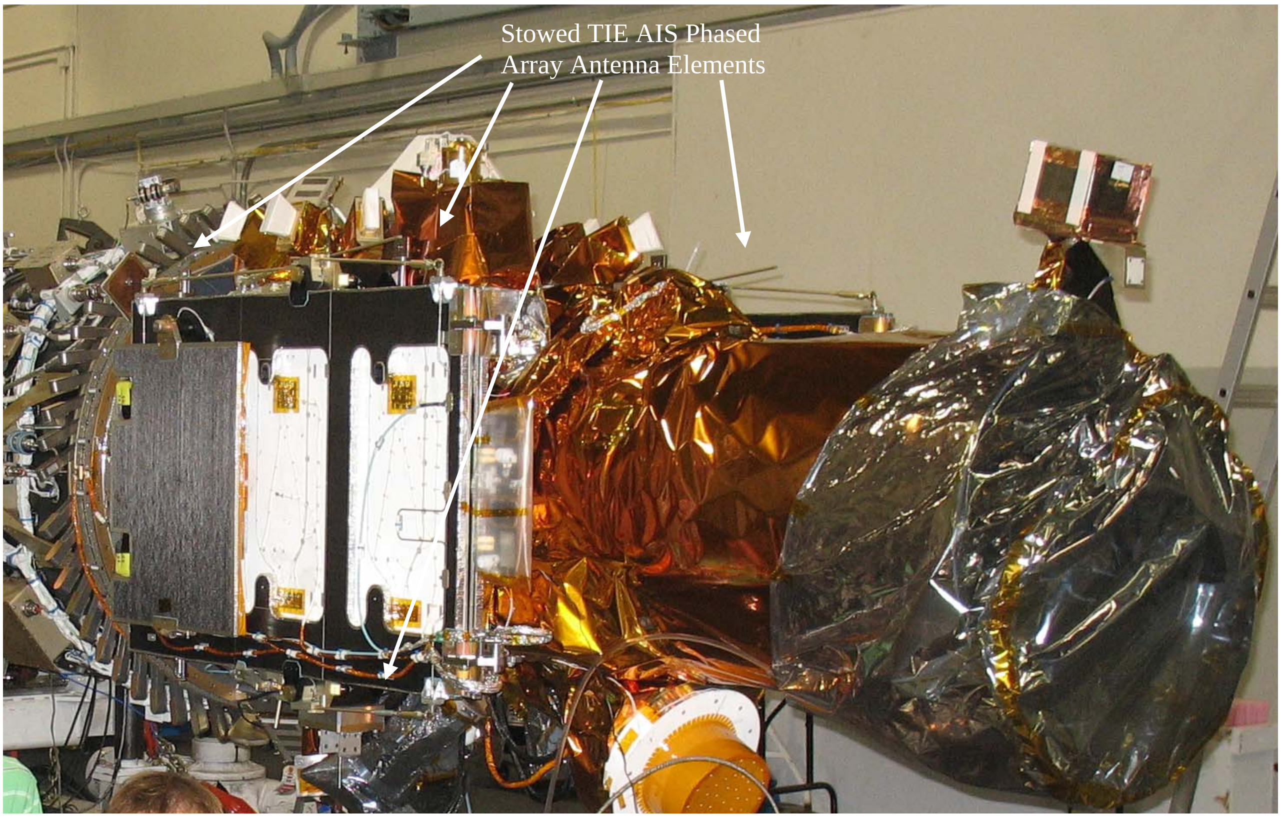

Figure 2. TIE AIS Antennas on the Stowed Solar Arrays

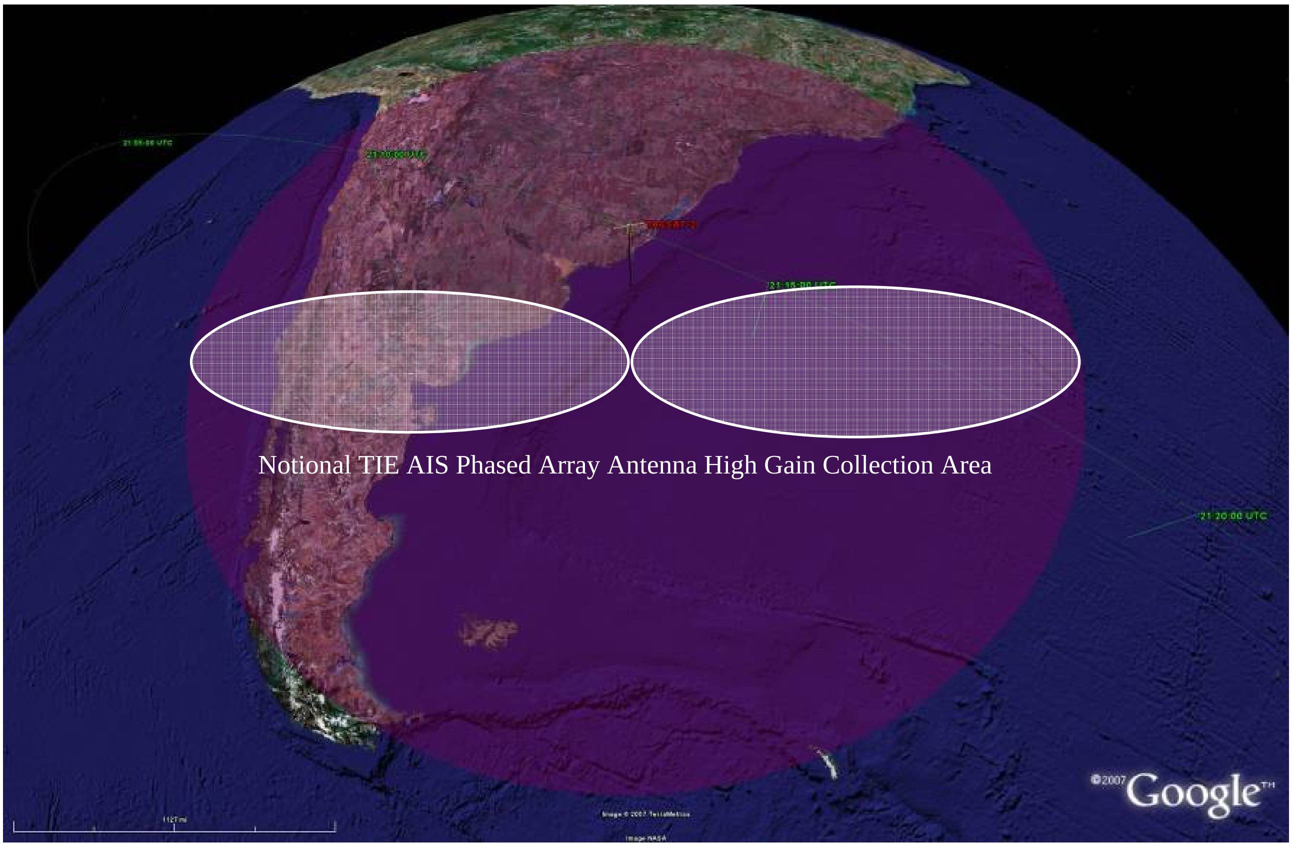

Figure 3. TIE AIS Phased Array Antenna Notional Instantaneous Field of View

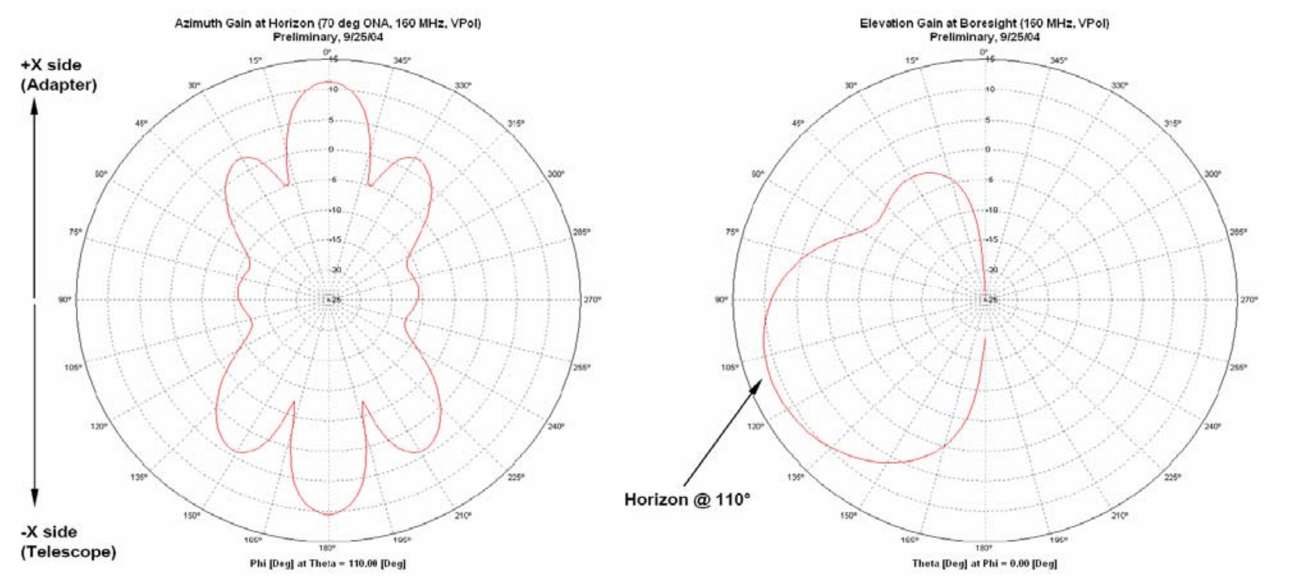

Figure 4. TIE AIS Phased Array Antenna Ideal Pattern

The AIS receiver system was designed to receive and digitize VHF RF signals, and to demodulate the messages on-board the spacecraft. The resulting binary messages were then encapsulated as standard NMEA-0183 message strings. These messages were functionally equivalent to the messages that a ship-based AIS receiver would have produced. The on-board demodulator process was instrumented to provide additional information about the demodulation process to include how many messages were not decoded due to a variety of issues such as frame errors, missing start flags, etc. On-board demodulation also provided a significant degree of data compression. The TIE payload software was modified on orbit to capture snapshots of analog-to-digital converter samples for use in detailed analysis on the ground. However, the resulting data files were large, and given the complexities of the host spacecraft, only a few of these snapshots were successfully captured and brought to the ground. The TIE team was in the process of working on updated software that would have made this process more efficient and result in smaller data files when the mission ended

1.4. AIS Overview

AIS transponders are used to help provide situational awareness for ships as they transit the oceans and move about in busy harbors. These messages include information such as the ship's Maritime Mobile Service Identities (MMSI) number, the name of the ship, it's heading and speed, the size of the ship, and other relevant information. AIS transponder systems are required by international treaty, insurance carrier requirements, and US law on many commercial vessels. AIS messages also provide situational awareness to regional authorities by alerting them before ships and cargoes enter their area of interest.

AIS signals are broadcast in the VHF marine band, and are intended to operate in line-of-sight range. From the mast of a ship the typical AIS reception area is about 1,200 square kilometers. However, from a UAV flying at an altitude of 10 kilometers, the area of reception for AIS message can increase significantly providing line-of-sight coverage of nearly 400,000 square kilometers. From a low Earth orbiting spacecraft, AIS messages can potentially be received over a very significant footprint, millions of square kilometers, as shown in Fig. 5.

AIS messages use a self organizing, time division multiple access (SOTDMA) communications technology that allows AIS transmitters that are within sight of each other to de-conflict their messages by scheduling their transmission into separate time slots. This is a critical decision in the design of the system, and effects collection platforms that see beyond the line-of-sight of surface based collection systems. A spacecraft will see many self organized networks of transponders that makes the self organizing feature, which is important for surface operations and co-channel de-confliction, ineffective for space collection applications. However, it is not necessary that every AIS message be received since the system retransmits information periodically to help minimize the number of missed messages. This information redundancy allows important information to be received even when a large percentage of messages from a single emitter are interfered with, or not successfully demodulated

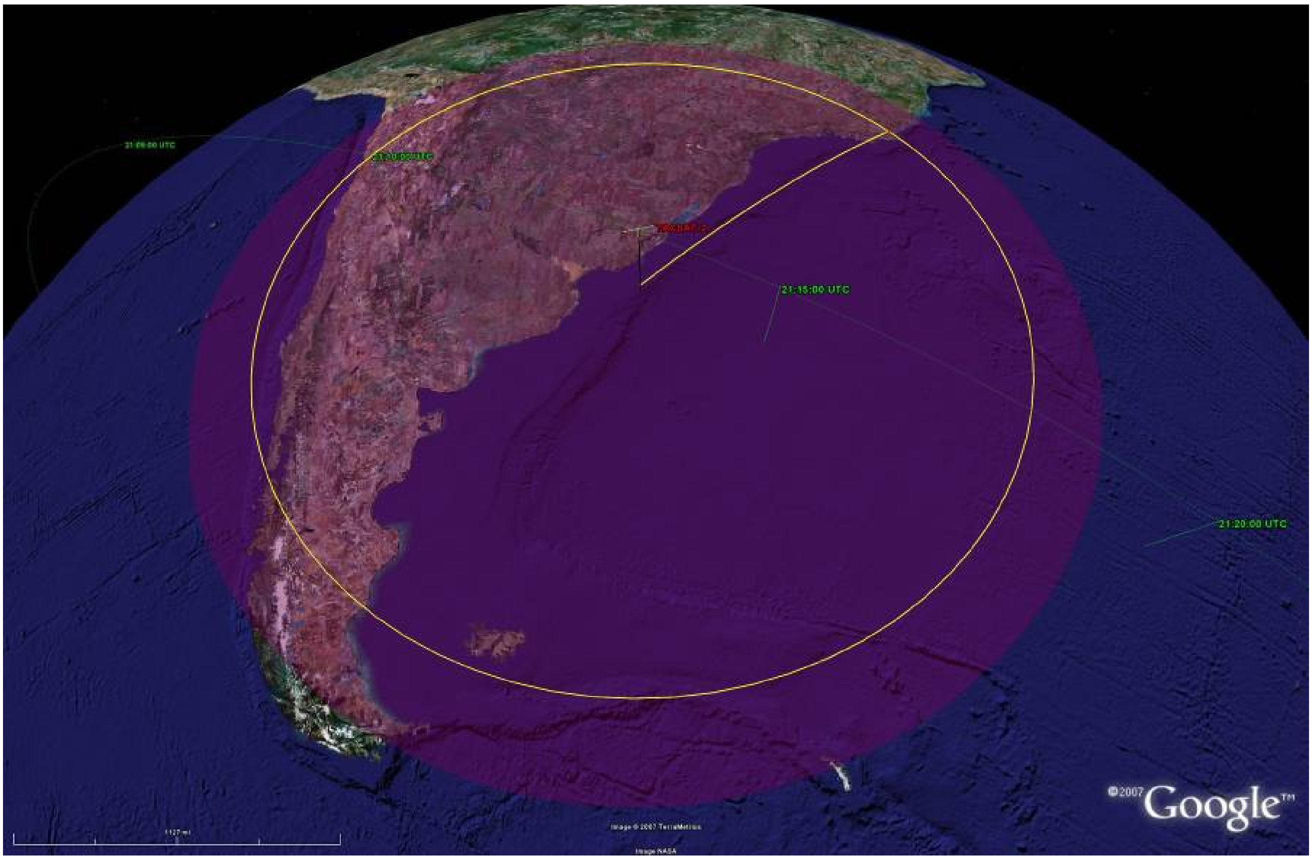

Figure 5. TacSat-2 TIE Payload Field of View

1.5. AIS Collection Experimentation

The TIE AIS investigations were divided into the following areas 1) phased array antenna orientation and configuration testing, 2) sampled RF data collection, 3) calibration data collection, 4) algorithm enhancements, and 5) long term data collection. Additional details of the initial plan for these investigations are shown in Tab. 1. Some of these investigations were conducted in parallel, while others required sequential collections with time between collections to allow for analysis of the data. There were many factors of collecting the AIS signal from space that were not fully understood, and were key reasons for the development of this payload. From the beginning the TIE team had planned to modify the TIE AIS experiments as data collection and analysis progressed, and our understanding of the problems evolved. While there were many combinations of settings to test, they were not all evaluated due to time and tasking constraints prior to the end of the mission.

2. RESULTS

Quantifying the performance of an AIS receiver system in space is a difficult undertaking; in particular, defining the metrics to quantify performance is a challenge. In a world with no other factors, performance might be quantified by the probability of intercept of a single message from a single emitter within the footprint of the collecting platform. Collecting ground truth information in order to help quantify that is a problem due to the varied networks for ground-based collectors. The community of experts examining AIS collection from airborne and space borne platforms is still evaluating the usefulness of different metrics.

From a global maritime awareness perspective, the ability to maintain information on a vessel's position and course is the key metric that flows down to the requirements for an AIS collection system. Ensuring that the revisit time is sufficient to maintain a persistent look at the behavior of a ship is critical, and would most likely require multiple spacecraft.

Multiple technical and policy issues delayed checkout of the TIE payload until April of 2007. This delay combined with the spacecraft's participation in two military exercises in support of the JMUA meant that little AIS data was collected by the TIE payload until the EUE commenced in late September of 2007.

In order to help quantify the performance metrics, TIE data was analyzed in two ways. Due to the data size, the bulk of the information was relayed to the ground as demodulated messages streams. Quantifying the receiver's performance with this data involved looking

Table 1. TIE AIS Investigations

AIS Test	Data Type	Geographic Region	Data Needs
Antenna orientation and configuration	Demodulated AIS messages	Ocean regions with emphasis on US coastal areas	~8 hours of collection time per combination
Sampled RF data collection	Low level samples before on-board demodulator	Areas where TIE AIS reception is poor, e.g. US coasts, and other areas to establish noise floor	Due to the large data volume, 20-60 seconds per collect, ~2 times per week
Calibration data collection	Low level samples before on-board demodulator	Sites where calibration equipment is located	Due to the large data volume, 20-60 seconds per collect, ~2 times per week
Algorithm Enhancements	n/a	Ocean regions	Statistically significant collections
Long term data collection	Demodulated AIS messages	Ocean regions	Statistically significant collections

at the out-of-band telemetry information from the demodulator, as well as message density and periodicity in areas of known high traffic density. Ground truth collection information was also used to further quantify the payload's performance.

The data that the TIE payload was able to collect confirmed that both co-channel and near band interference present challenges to collecting the AIS signal from space. The TIE signal collection performance over much of the Earth was very good. This was true even in areas of high ship traffic density such as the Straits of Gibraltar, the Arabian Sea, and the South China Sea as shown in Fig. 6, 7, and 8. However, in other areas receiver performance was unsatisfactory, and even dropped to zero in some cases. While TIE experience both co-channel and near band interference, the most disabling interference appeared to be the near band interference caused by high power radiations in adjacent bands of the receiver. These transmissions appeared to be mostly of a continuous wave nature. When these high duty cycle transmissions were present the receiver performance dropped off to zero. This interference was probably seen over North America, specifically along the US coasts as shown in Fig. 9 and 10, where performance clearly dropped very low on the West coast, and to zero along the East coast. In the Caribbean, and further out into the Atlantic, this performance drop off was not seen as shown in Fig. 11. Given the data that has been analyzed to date we concluded that the AIS receiver performed reasonably well in a message-on-message signal environment

2.1. Phased Array Testing Results

The purpose of the phased array antenna orientation and configuration testing was to determine how the antenna directionality and gain affected system level reception and demodulation of AIS messages. While 10dB of gain is not a great deal, the TIE team surmised that the directivity would act as a filter that helped in some co-channel interference scenarios. Some of the sources of this interference include; unintentional interference caused by other licensed spectrum users, unintentional interference caused by other SOTDMA users who cannot see each other and therefore cannot self de-conflict, and other near band interferers. The interference problem is more challenging in a space environment due to the large footprint on the earth visible to the spacecraft, and the fact that the filters that help eliminate interference sources need to be wider in the space application to account for the Doppler shift experienced from a spacecraft. It was known in the TIE hardware development that the design did not utilize ideal RF and IF filters. The filters needed were not available from manufacturers in time to support the original delivery requirements of the payload to the spacecraft integrators.

The initial array testing plan focused on four possible orientations. Experience with those orientations showed that other combinations needed to be investigated to fully examine the problem set, and to quantify the ability of the array to help mitigate interference issues. The four original antenna orientations were 1) the baseline orientation with the spacecraft phased array beam aligned with the spacecraft velocity vector, i.e. beam lobes in-track, 2) spacecraft phased array at 45 degrees to the spacecraft velocity vector, 3) spacecraft phased array at 90 degrees to the spacecraft velocity vector, i.e. beam lobes cross track, and 4) spacecraft in sun track mode, which resulted in a varying size beam on the ground that was much smaller than the standard beam. In this orientation the other end of the beam was pointed into space. The results of these tests are summarized in Tab. 2

Figure 6. TIE AIS Data From a Single Pass Over the Eastern Atlantic and Straits of Gibraltar

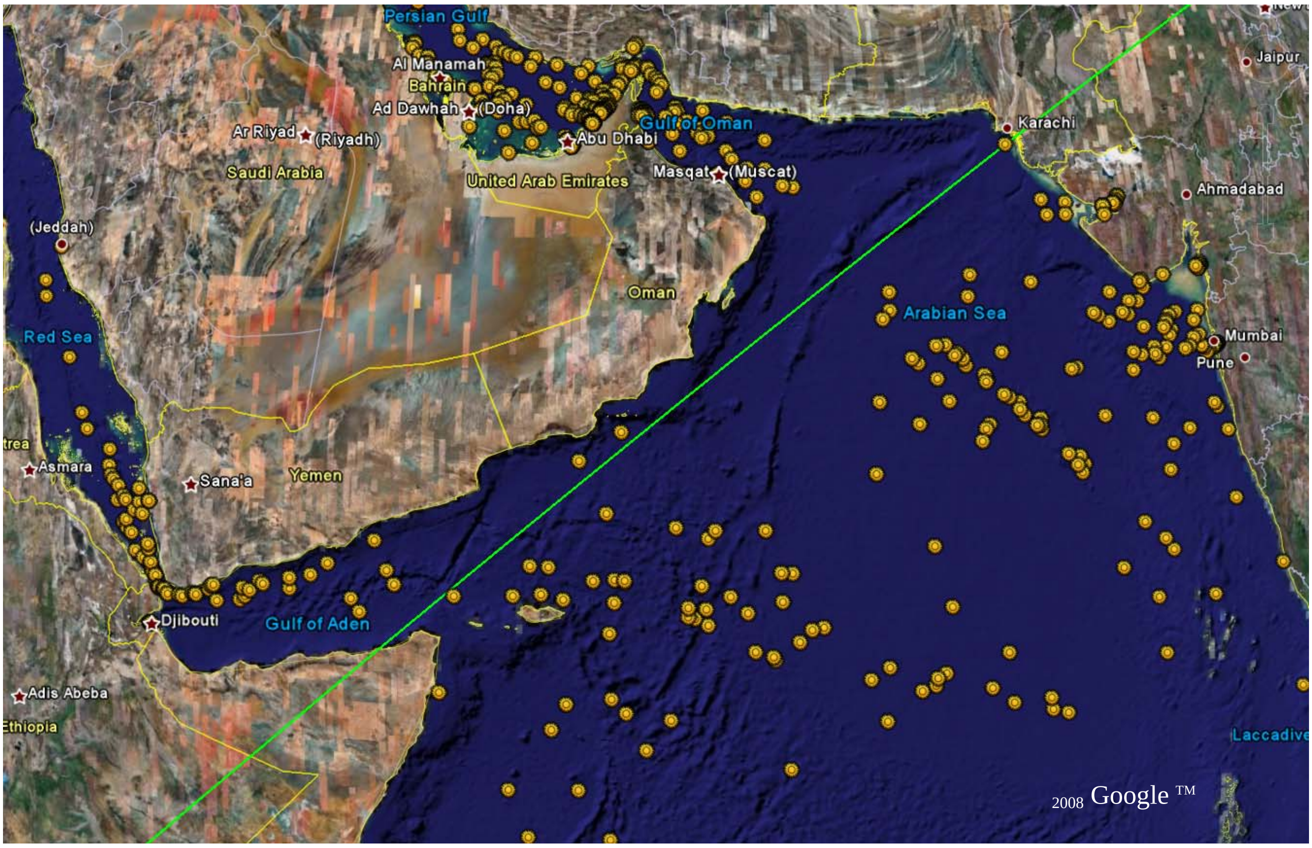

Figure 7. TIE AIS Data From a Single Pass Over the Arabian Sea and Persian Gulf

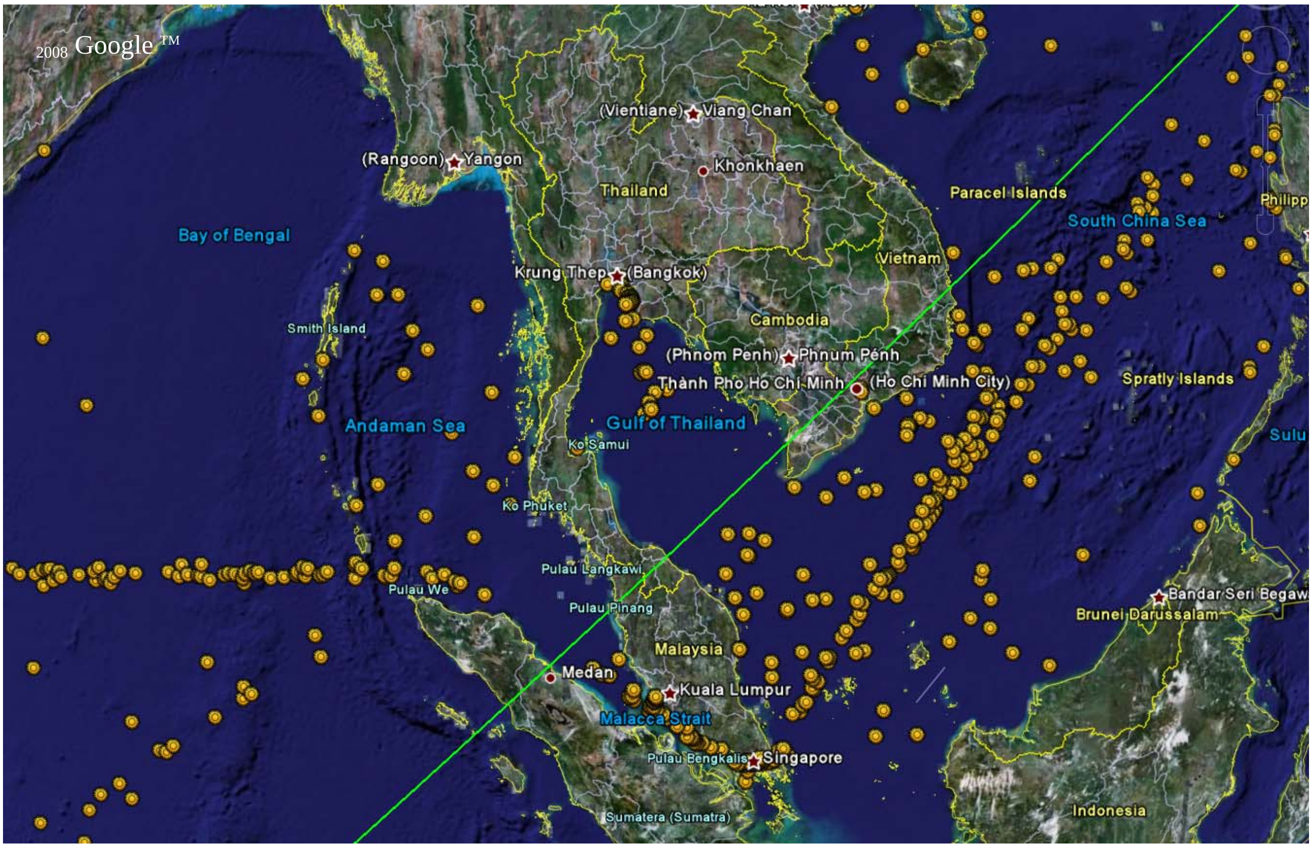

Figure 8. TIE AIS Data From a Single Pass Over the South China Sea

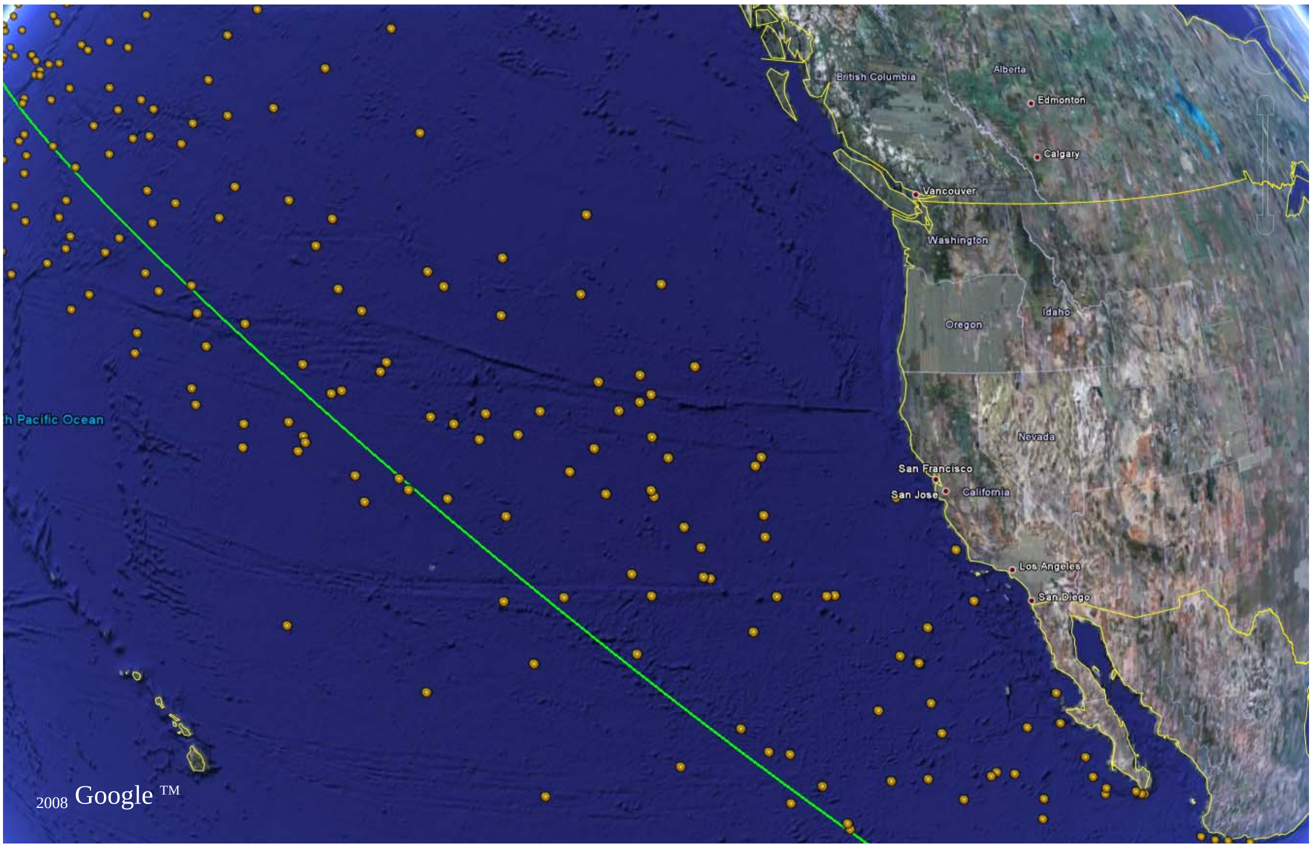

Figure 9. TIE AIS Data From a Single Pass Over the US West Coast

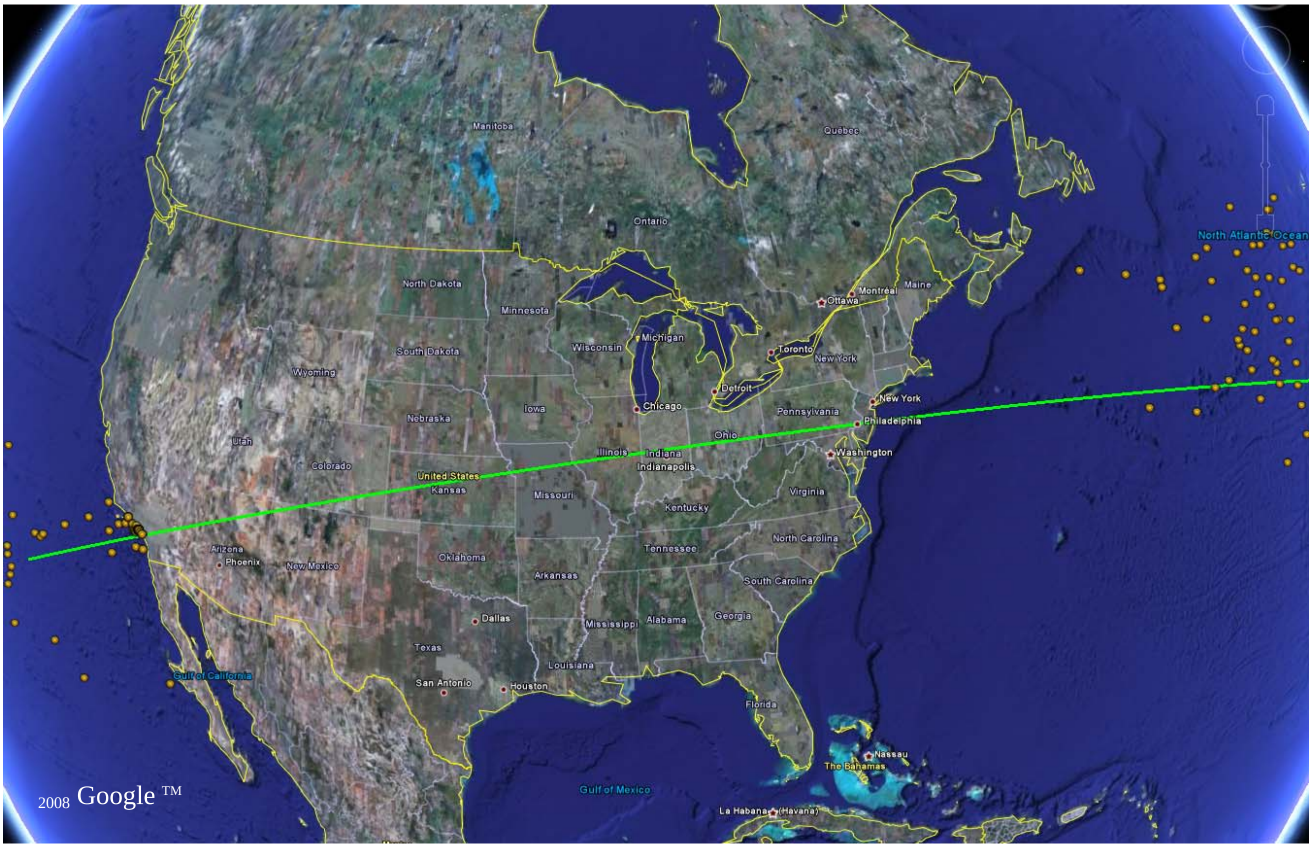

Figure 10. TIE AIS Data From a Single Pass Over the US

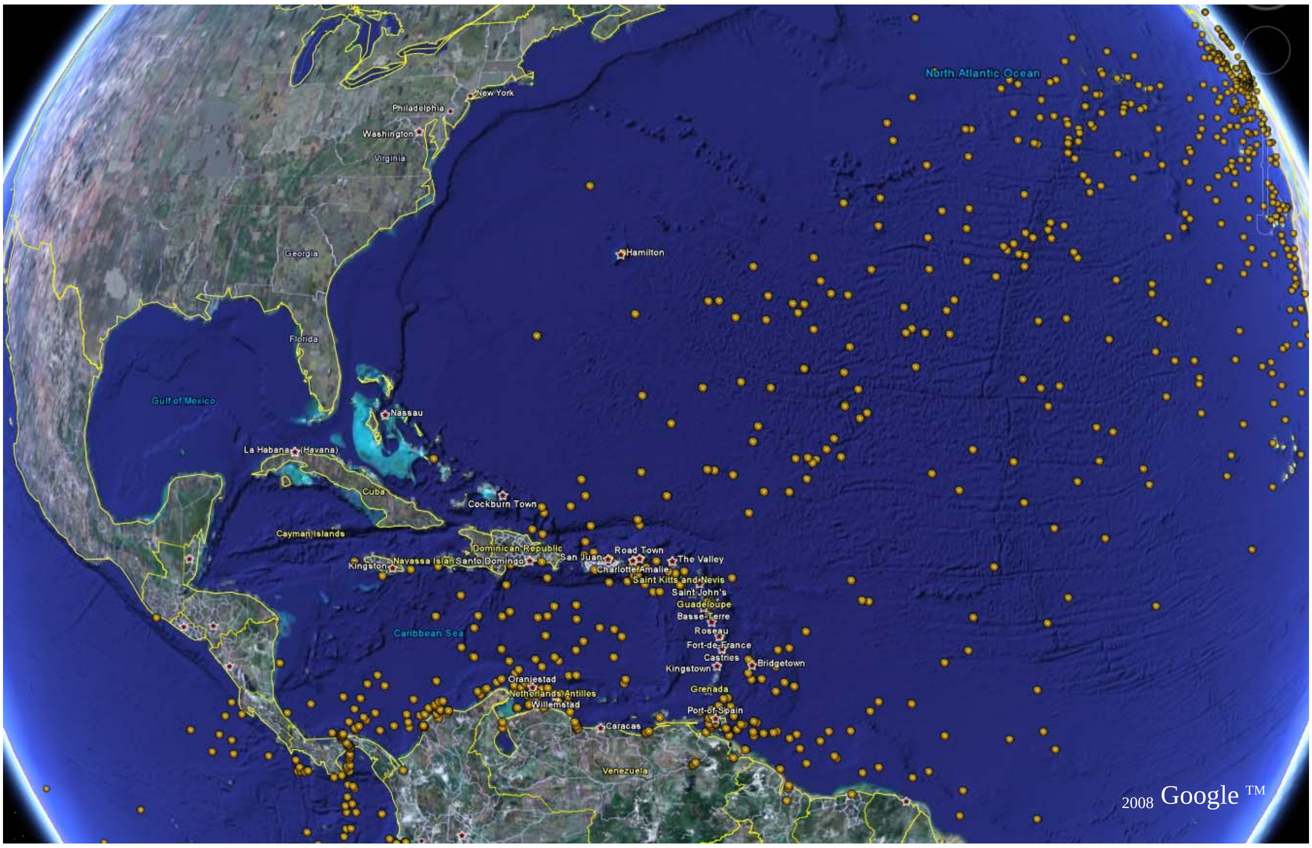

Figure 11. TIE AIS Data From a Single Pass Over the Caribbean and Mid-Atlantic

Table 2. TIE AIS Phased Array Antenna Test Configurations and Results

Configuration	Tag Description	Comments
Baseline orientation with spacecraft phased array along the velocity vector	“ais_eclipse”	34 collections made in this mode Total messages 64,320 Total duration 45,912.491 seconds Peak rate= 3.47 messages/sec Average rate 1.40 messages/sec
Spacecraft phased array at 90 degree angle to spacecraft velocity vector	“ais_eclipse_rot90”	15 collections made in this mode Total messages 2,4561 Total duration 22,730.399 seconds Peak rate 1.49 messages/sec Average rate 1.08 messages/sec
Spacecraft phased array at 45 degree angle to spacecraft velocity vector	“ais_eclipse_rot45”	19 collections made in this mode Total messages 33,506 Total duration 28,940.173 seconds Peak rate 1.47 messages/sec Average rate 1.15 messages/sec
Spacecraft configured to its optimal sun-tracking mode (without regard to AIS antenna pointing)	“ais_eclipse_suntrk”	8 collections made in this mode Total messages 13,949 Total duration 24,217.419 seconds Peak rate 1.54 messages/sec Average rate .57 messages/sec
A mode optimized to put the smallest AIS gain antenna pattern on the earth	“ais_spot” and “ais_eclipse_spot”	6 collections made in this mode Total messages 5,167 Total duration 11,458.544 seconds Peak rate .73 messages/sec Average rate .45 messages/sec
TS-2 imaging mode orientation without regard to AIS pointing	“ais_imaging”	1 collection made in this mode Total messages 1,637 Total duration 2,272.666 seconds Average rate .72 messages/sec
Standard AIS collection orientation using a single antenna for omni coverage	“ais_eclipse_omni”	2 collections made in this mode Total messages 121 Total duration 2,246.419 seconds Average rate .05 messages/sec
Standard AIS collection using the wideband mode of the digital demodulator	“ais_eclipse_wide”	9 collections made in this mode Total messages 649 Total duration 8,861.977 seconds Average rate .07 messages/sec
Standard AIS collection using changing the demodulator limiter function on and off	“ais_eclipse_limA on/off limb on/off”	LimA on provided about 10% more messages than LimA off Similar performance with LimB testing

An analysis of the different phased array collection modes shows that when using the metric of messages per second the baseline AIS collection mode provided the best results. Using the metric of messages per second however may not be the best metric to use. Other collection modes including “ais_eclipse_rot90” appeared to provide more unique MMSI numbers per second. Defining what the most appropriate system performance metric is depends on the mission objective, and could include total number of collects, maximizing unique MMSI numbers collected, or tracking a particular vessel.

2.2. Sampled RF Data Collection Results

The sampled RF data collection mode was the TIE receiver mode that allowed detailed recording of the intermediate frequency (IF) seen by the spacecraft in its demodulator bands. Having access to the collected RF allowed the use of more sophisticated tools on the ground to examine the data for anomalies and other issues that may have hindered the performance of the demodulator. A spectrograph of a sample of the TIE sampled RF data is shown in Fig. 12. Fig. 13 shows a display of one of the tools used to analyze the sampled RF data.

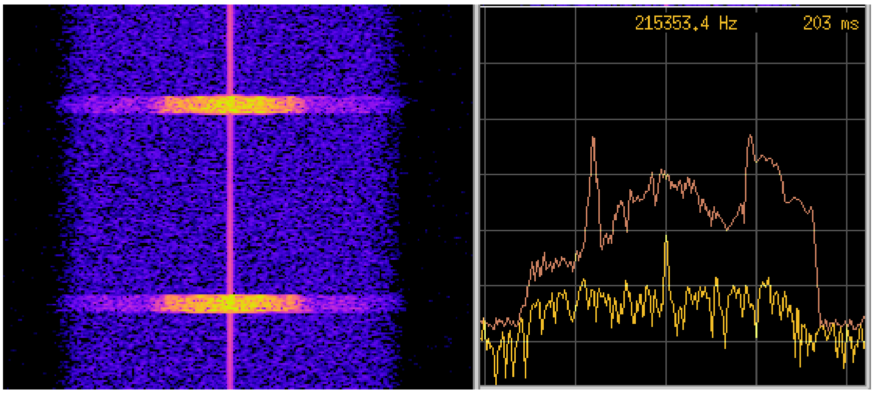

Figure 12. TIE AIS Spectrograph of Sampled RF Data

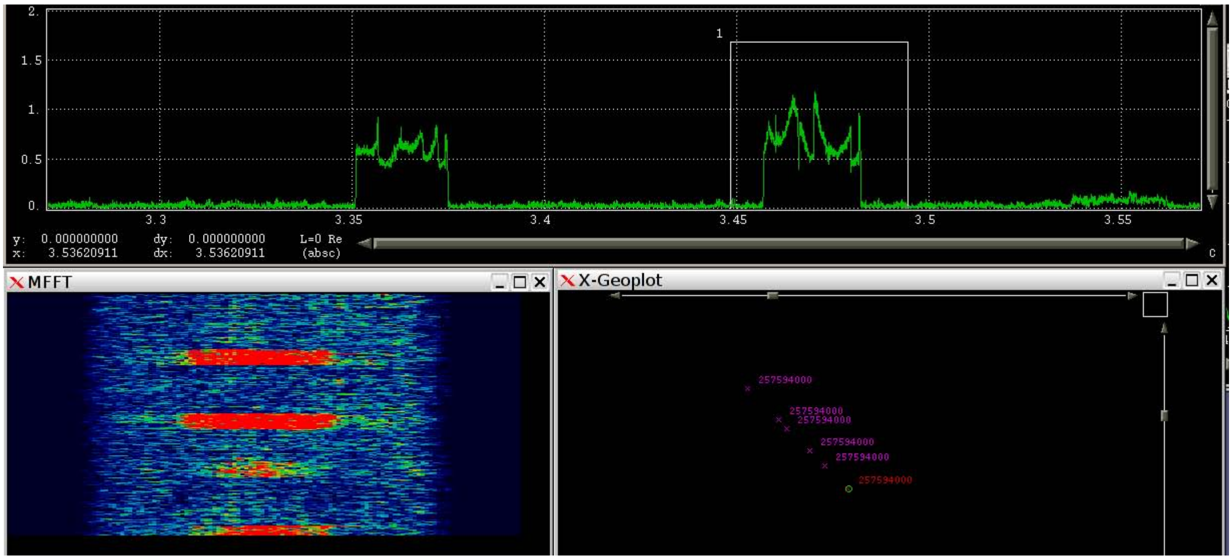

Figure 13. Screen Display of Sampled RF Data Analysis Tool

The trade off in using this mode was that the captured analog to digital data files were very large. About one megabyte of data was generated for every second of data recorded. This created challenges in downlinking the files, and successfully getting data products from the spacecraft. A major part of the sampled RF task was to schedule a ground truth asset for each sampled RF testing event. While some successful sampled RF collection events occurred on the spacecraft, none of these collections coincided with collections by the ground truth asset.

Given various performance indications that were noted around CONUS, there were combinations of antenna orientation testing and sampled RF collection that were desired that may have provided some insight into how the noise floor from interfering signals changed while the spacecraft antenna beam traversed the Earth.

2.3. Calibration Data Collection Results

This data collection mode was a special case of the sampled RF collections. The calibration data collection added a cooperative emitter to transmit in-band or slightly off-band up to the spacecraft during a sampled RF collection to explore the reception of a known signal being generated in the presence of other signals in the environment. No calibration data collections were performed before the end of the mission.

2.4. Algorithm Enhancements

Insufficient data collection and analysis was completed before the end of the mission to allow for the development of enhanced algorithms, although several options such as intersymbol interference compensation were being evaluated. The AIS demodulator algorithm used on the TIE payload was a basic, one bit differential type. There are several different GMSK demodulator algorithms that provide better performance, but at the cost of additional processing power and computational

complexity. A great deal of study is being done globally for the best GMSK demodulating algorithms not only for AIS signals, but also for other applications such as GSM cellular phones that stand to benefit from improvements in demodulation.

While the TIE team was unable to perform some of the modifications of the algorithms on-orbit, this work is continuing on airborne platforms being outfitted with equipment similar to the TIE hardware.

2.5. Long Term Data Collection

Assembling a statistically relevant data set requires the collection of a substantial amount of data over a long period of time from geographically diverse locations using multiple system configurations. While more AIS data was collected during the last two months of the mission than during the preceding nine months, most of the data was collected during a two week period in mid-October. Fig. 14 shows all of the EUE AIS collection events, tasked and untasked, as a function of date. Fig. 15 and 16 plot the contacts received and the cumulative contacts as a function of date. Much additional work would be required before the long term data collection task could be considered complete.

3. CONCLUSIONS AND RECOMMENDATIONS

The TIE payload successfully demonstrated the ability to collect the AIS signal from a low Earth orbiting spacecraft. By providing global AIS tracks, the TIE payload supplied a supplemental data source for world wide vessel tracking. AIS signal reception from space allows for the tracking of cooperative vessels off-shore and in mid-ocean, a capability not available from other AIS data sources, making the capability highly desirable. Nevertheless, several factors limited the utility of the TIE data. A key shortfall of the system was the inability to receive AIS signals from vessel in ocean regions of high interest to the US Coast Guard, specifically the Eastern seaboard and Gulf of Mexico. Limited satellite time for dedicated AIS use and a premature end to the EUE prevented sufficient analysis to identify the source of this problem. Limited data suggests that strong off-channel interference prevented successful demodulation in these regions. Future designs should place a high priority on acquiring RF filters that tightly bracket the AIS operating channels.

From the experience gained operating the TIE AIS receiver, and analyzing the data collected, the TIE team identified additional techniques and capabilities in the receiver/demodulator and with the phased antenna array that warranted further investigation. While some tests were unique to the TIE implementation and could not be performed because of the premature end of the mission, others are potentially applicable to future AIS receiver developments.

Sufficient evidence exists that the receiver/demodulator performance was degraded by mutual interference between widely separated AIS transmitters. Off-tuning the digital channel filters to exploit the frequency separation caused by satellite motion Doppler might have increased the number of messages received from some emitters in dense co-channel environments. An enhanced receiver could implement a set of optimal channel filters distributed across the Doppler widened channel. The mission ended before TIE was operated with message validation disabled; it is likely that many additional messages would have been received, and in many cases, that these errors could have been detected and corrected using the inherent message redundancy of AIS.

Although the TIE phased array combiner allowed further arrangements of the antenna elements, forming alternate lobes and nulls, and allowing various pairs of monopoles to be used as omnidirectional antennas, these capabilities were not exercised before the mission ended. Additional testing of omnidirectional antenna configurations in various vehicle orientations would be useful.

While some of the capabilities of the TIE AIS payload were never exercised, much data was collected in many important receiver configurations and in various space vehicle orientations. TIE's AIS payload successfully demonstrated the ability to collect AIS transmissions from space and the utility of these messages in the global monitoring of ship traffic.

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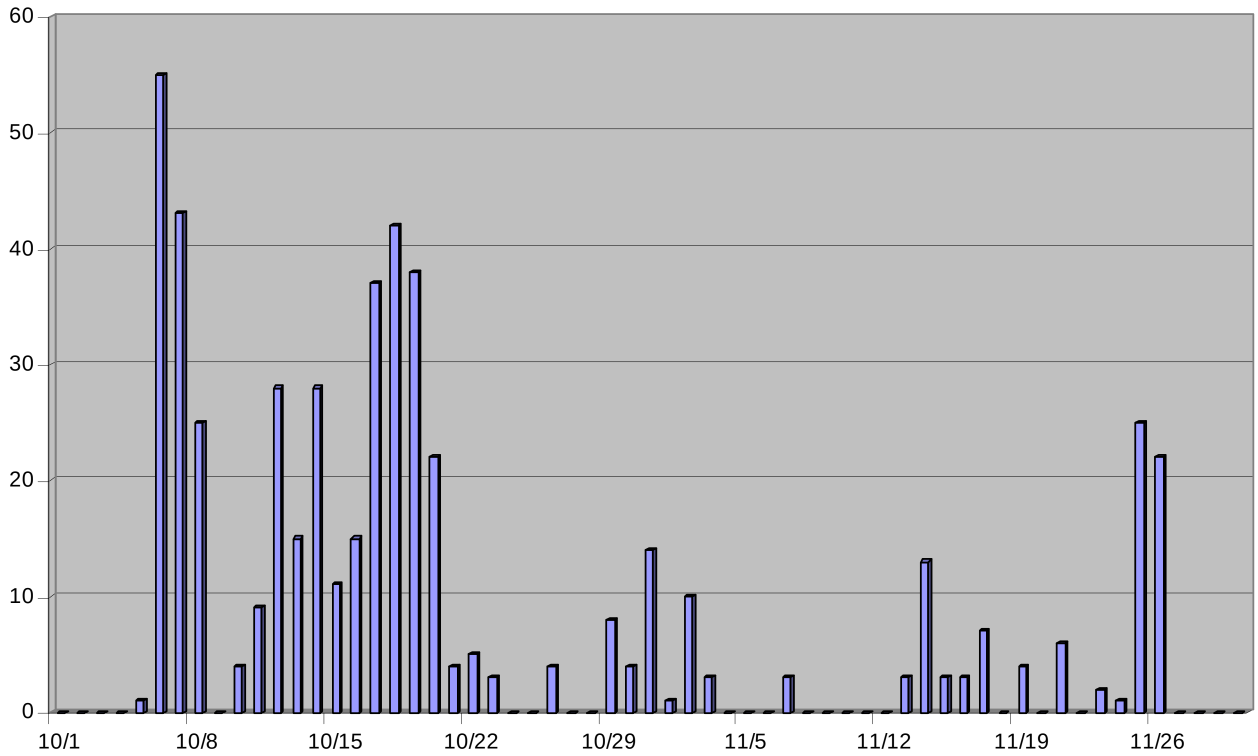

Figure 14. EUE AIS Collection Events by Date

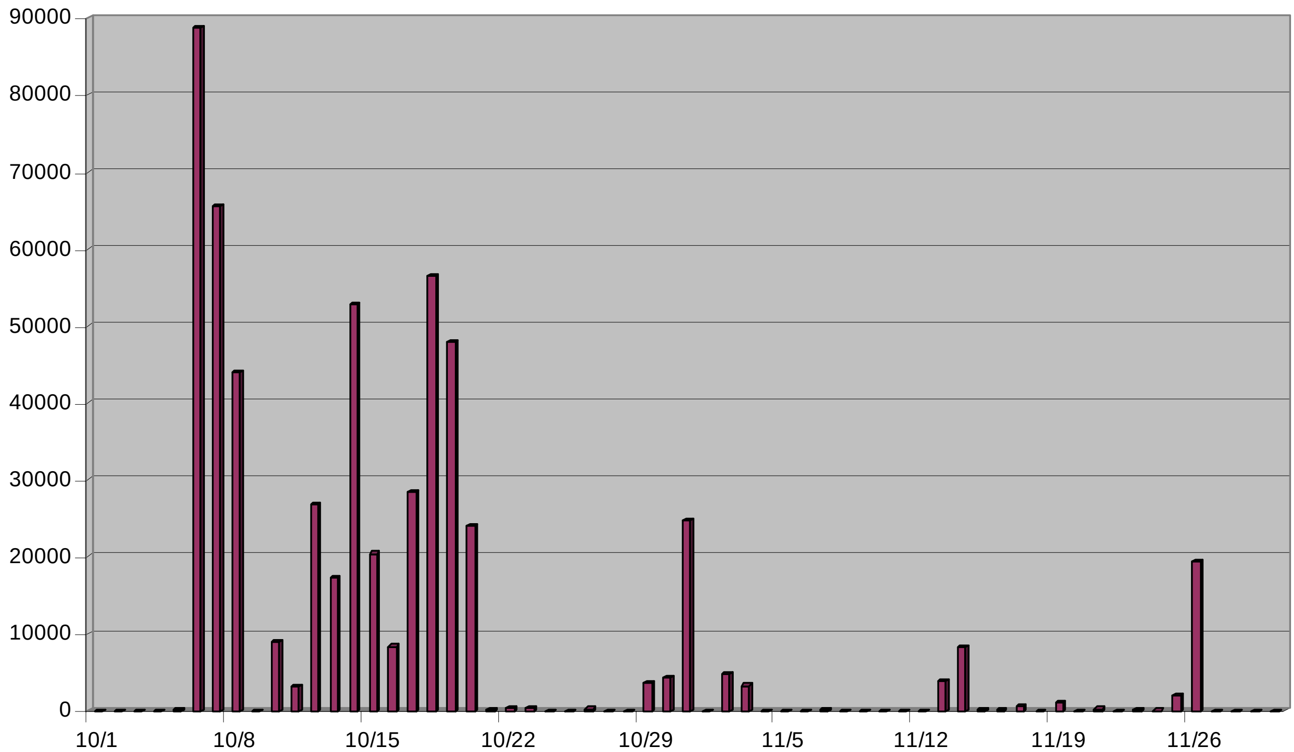

Figure 15. EUE AIS Contacts by Date

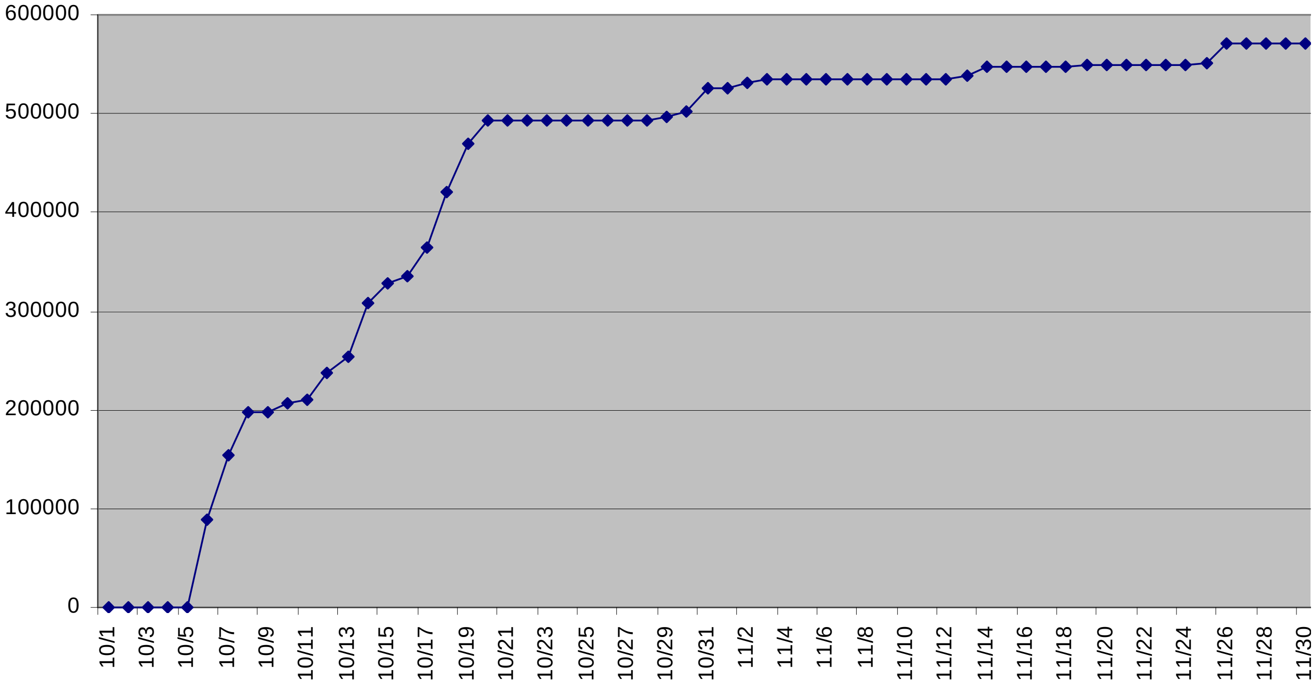

Figure 16. EUE Cumulative AIS Contacts by Date